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ORIGINAL ARTICLES

Laminar Burning Characteristics Of Biogas-Air Mixtures In Spark Ignited Premix Combustion

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ABSTRACT

Laminar burning velocities of biogas-air mixtures in premixed combustion have been studied to elucidate the fundamental flame propagation characteristic of biogas as a new alternative and renewable fuel. The results are compared with those from a methane-air flame. Biogas is a sustainable and renewable fuel that is produced in digestion facilities. The composition of biogas discussed in this paper consists of 66.4% methane, 30.6% carbon dioxide and 3% nitrogen. Burning velocity was measured using a photographic technique in a high pressure fan-stirred bomb, the initial condition being at room temperature and atmospheric pressure. Based on this experimental investigation, the laminar burning velocities of biogas-air mixtures were 0.2086 m/s for lean (□=0.8), 0.2638 m/s for stoichiometric (□=1.0) and 0.1864 m/s for rich (□=1.2) conditions. Compared to a methane-air mixture, the presence of carbon dioxide and nitrogen causes a reduction in the laminar burning velocity for two reasons. The dilution effect leads to a lower concentration of reactive species in the fuel-air mixture for a given equivalence ratio, which leads to a lower overall chemical reaction rate of bimolecular reactions in the fuel oxidation reaction mechanism. Also, the presence of this additional inert gas will absorb some of the heat generated, thus lowering the flame temperature which in turn will tend to reduce the overall rate of many of the chemical reactions within the fuel oxidation mechanism. These effects lead to a different behaviour in burning velocity of biogas as a function of equivalence ratio. Whereas a rich (□=1.2) methane-air mixture has a higher burning velocity than a lean (□=0.8) mixture, the reverse is the case for the equivalent biogas-air mixtures where the lean mixture has a higher burning velocity than the rich mixture. This is a consequence of the rich biogas-air mixture having a higher fraction of the carbon dioxide and nitrogen components from the fuel compared to the lean biogas-air mixture, and shifts the optimum equivalence ratio for operation of a biogas-air mixture to a leaner mixture than would be the case for methane-air mixtures.

Key words: Sustainable energy; Biogas; Premix combustion; laminar burning velocity.

Introduction

The consumption of fossil fuels in internal combustion engines and the associated environmental impacts are now worldwide concerns. These concerns have stimulated research into more environmentally friendly alternative fuels that can replace fossil fuel. Biogas as "Powergas" is an alternative fuel. The aim of using biogas is diversification of energy supply, the reduction of carbon dioxide emissions and advancement of rural development. Biogas is a sustainable and renewable fuel that is produced in digestion facilities. It does not contribute to the increase in atmospheric carbon dioxide concentrations because it comes from an organic source with a short carbon cycle and is a green solution in the development of sustainable fuels (Anggono W., 2012).

The Kyoto protocol was intended to reduce green house gas emissions, and to futher this objective, research into biogas combustion in engines and gas turbines has had good results (Lafay Y., 2007; Nathan. S.S. 2010; Porpatham E., 2008). However, the laminar burning velocity of biogas, being a fundamental characteristic of a fuel has not been studied yet. Thus, the aim of this paper is to investigate its laminar burning characteristics. The laminar burning velocity of biogas is interesting because of its chemical composition. Based on chemical analysis, the composition of the biogas produced in East Java, Indonesia is 66.4% methane, 30.6% carbon dioxide and 3% nitrogen. Methane is a flammable gas, whereas, nitrogen and carbon dioxide are inhibitors (Anggono W., 2012; Ilminnafik N., 2011).

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Demands for improving engine design and for replacing fossil fuels in terms of power output, efficiency and emissions control, require an improved fundamental understanding of the combustion processes that occur within the internal combustion engine. An important characteristic is the burning velocity, which directly affects pressure development and is often expressed in terms of laminar burning velocity (Anggono W., 2012; Gillespie L., 2000; Gu. X.J, 2000; Bradley D., 1998; Serrano C., 2008; Marshall. S.P., 2011). The laminar burning velocity is the most important flame propagation characteristic in spark ignited premixed combustion and as the fundamental flame propagation characteristic of biogas requires further study, this paper looks into this matter with view to a better understanding of a new alternative and renewable fuel. The results are compared with methane-air mixture experiments to emphasize the contrast between the burning velocity of methane-air mixtures and biogas-air mixtures.

Experimental Methods:

The laminar burning velocity of biogas premixed combustion was measured in the Leeds Mk II high pressure fan-stirred combustion vessel within the school of Mechanical Engineering, as shown in Fig. 1. Initially, all the experiments in this paper were performed at room temperature, atmospheric pressure and various equivalence ratios (□) from lean (□=0.8) to rich (□=1.2) mixtures rising by 0.2 for each experiment. The bomb was a spherical stainless steel vessel of 380 mm diameter, with three pairs of orthogonal windows each of 150 mm diameter and was equipped with four fans driven by electric motors (Anggono W., 2012; Gillespie L., 2000; Gu. X.J, 2000; Bradley D., 1998; Serrano C., 2008). Biogas used in this experiment had a composition as shown in Table. 1.

Table 1: Composition of Biogas.

Species	%
Methane	66.4
Carbon dioxide	30.6
Nitrogen	3.0

The fuel-air mixtures in the Mk II combustion bomb were centrally ignited and flame propagation was recorded by a high speed schlieren cine-photography using a Photosonics Phantom digital camera as shown in Fig. 2, operating at a rate of 2500 frames/s with a resolution of 768 x 768. The flame radius was calculated as that of a circle encompassing the same area as that enclosed by the schlieren imaged flame.

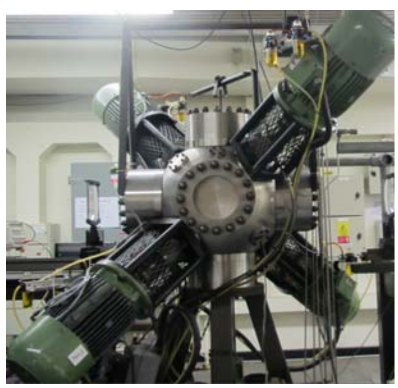

Fig. 1: Mk2 Combustion Bomb.

Fig. 2: High Speed Schlieren Cine-Photography.

The laminar burning velocity for a spherically expanding flame can be deduced from the schlieren photographs, the stretched flame velocity (S_n) can be derived from the flame radius versus time data as: $S_n = dr_u/dt$, where r_u is the flame radius in the Schlieren photographs and t is the elapsed time from spark ignition. The flame stretch rate α is defined as $\alpha = d(\ln A)/dt = (dA)/(A\ dt)$, where A is the area of the flame. In the case of a spherically propagating premixed flame, the flame stretch rate can be calculated by $\alpha = (2/r_u)(dr_u/dt)$. A linear relationship between flame speed and the total stretch exists, and this is quantified by burned gas of Markstein length, L_b, and is defined at the radius, r_u, such that: $S_n – S_s = L_b\ \alpha$, where S_s is the unstretched flame speed, and is obtained as an intercept value of S_n at $\alpha = 0$ in the plot of S_n against α. The gradient of the best straight line fit to the experimental data gives L_b. The unstretched laminar burning velocity, u_l, was deduced from S_s using $u_l = S_s\ (\rho_b/\rho_u)$, where ρ_b is the density of the burned gas mixtures and ρ_u is the density of the unburned gas mixtures (Anggono W., 2012; Gillespie L., 2000; Gu. X.J, 2000; Bradley D., 1998; Serrano C., 2008)

Results And Discussion

The flame propagation for lean (□=0.8), stoichiometric (□=1.0) and rich (□=1.2) biogas-air mixtures were observed to produce a propagating flame. The images resulting from the spherical flame propagation within the combustion bomb are shown in Fig. 3 to Fig. 5.

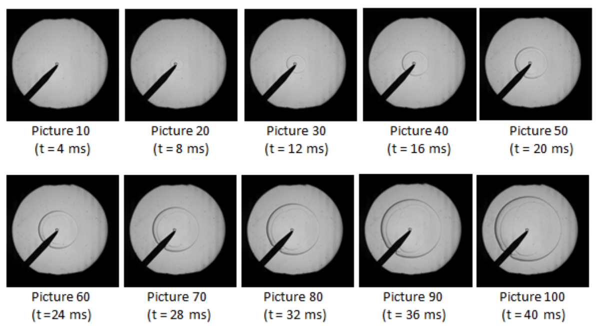

Fig. 3: Flame Propagation in Lean (□=0.8) Biogas-Air Mixtures.

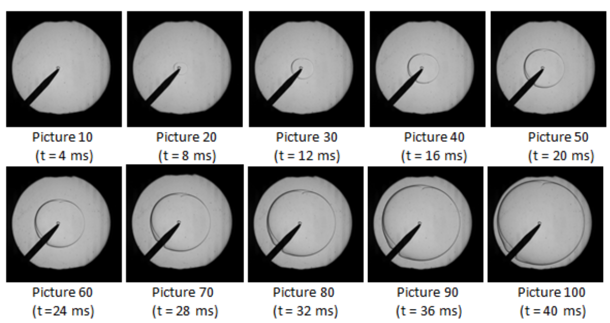

Fig. 4: Flame Propagation in Stoichiometric (□=1.0) Biogas-Air Mixtures.

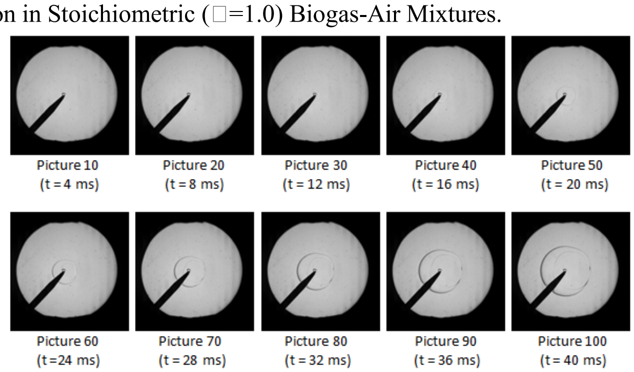

Fig. 5: Flame Propagation in Rich (□=1.2) Biogas-Air Mixtures.

The radius of the spherical flame propagation in Fig. 3 to Fig. 5 are presented in Fig. 6 as a function of elapsed time. Based on the experimental result and the calculation as mentioned in the experimental method and previous studies (Anggono W., 2012; Gu. X.J, 2000; Serrano C., 2008), the laminar burning velocities of biogas-air mixtures in premixed combustion were 0.2086 for lean (□=0.8), 0.2638 m/s for stoichiometric (□=1.0) and 0.1864 m/s for rich (□=1.2) biogas-air mixtures.

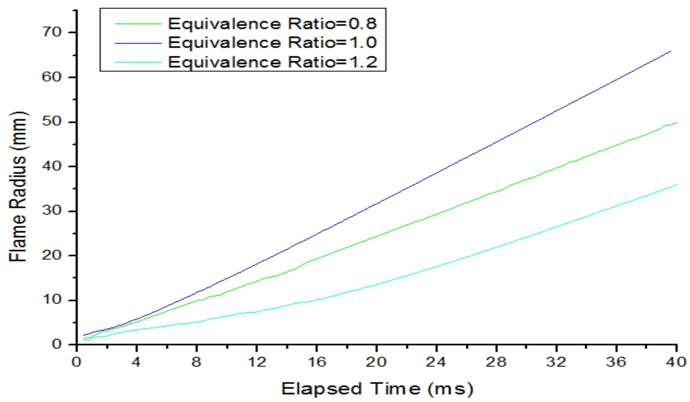

Fig. 6: Flame Radius vs Elapsed Time of Biogas-Air Mixtures.

For comparison, the laminar flame propagation of methane is also presented and the images resulting from the spherical flame propagation within the combustion bomb are shown in Fig. 7 to Fig. 9. The lean (□=0.8), stoichiometric (□=1.0) and rich (□=1.2) methane-air mixtures were observed to produce a propagating flame.

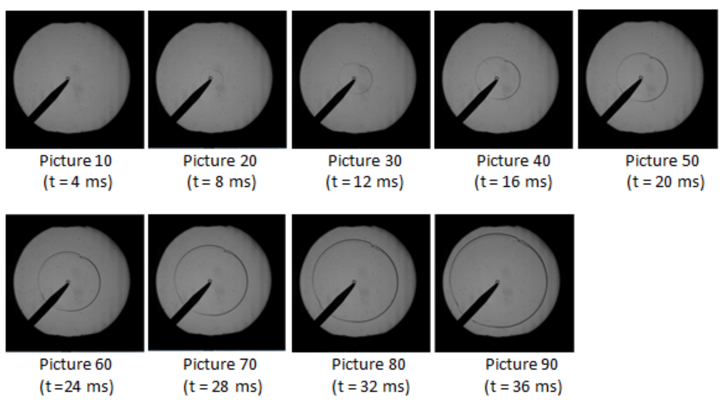

Fig. 7: Flame Propagation in Lean (□=0.8) Methane-Air Mixtures .

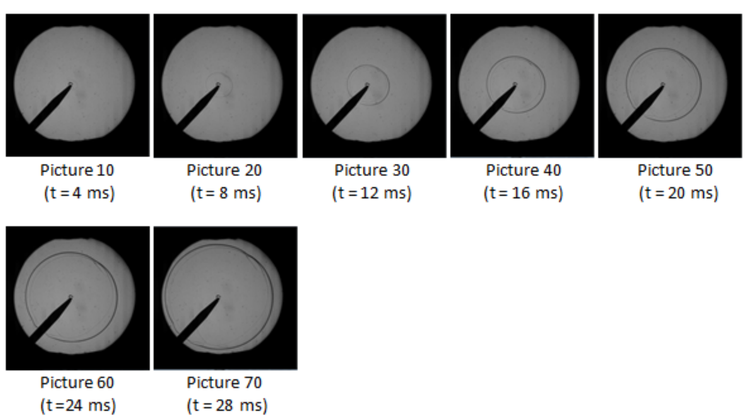

Fig. 8: Flame Propagation in Stoichiometric (□=1.0) Methane-Air Mixtures.

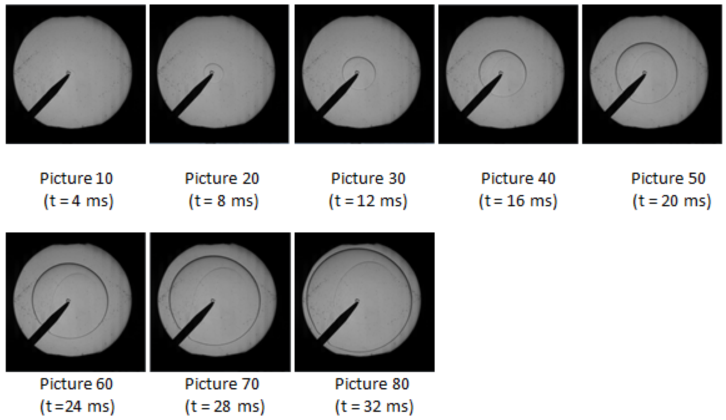

Fig. 9: Flame Propagation in Rich (□=1.2) Methane-Air Mixtures.

Based on the experimental results and the same calculations and method for the laminar burning velocity of the various equivalence ratios of biogas-air mixtures, the laminar burning velocities of the methane-air premixed mixtures have been measured. The laminar burning velocities were 0.2749 m/s for lean (□=0.8), 0.3527 m/s for stochiometic (□=1.0) and 0.3082 m/s for rich (□=1.2) methane-air mixtures, which are in agreement with previous studies (Anggono W., 2012; Gu. X.J, 2000; Aung K.T., 1995). A summary of the results from biogas and methane are shown in Table 2 and Fig. 10.

Table 2: Laminar Burning Velocities of Methane-Air Mixtures and Biogas-Air Mixtures Comparison Results.

Methane, pressure = 1 Atm		Biogas, pressure = 1 Atm	
□	Laminar burning velocity (m/s)	□	Laminar burning velocity (m/s)
0.8	0.2749	0.8	0.2086
1.0	0.3527	1.0	0.2638
1.2	0.3082	1.2	0.1864

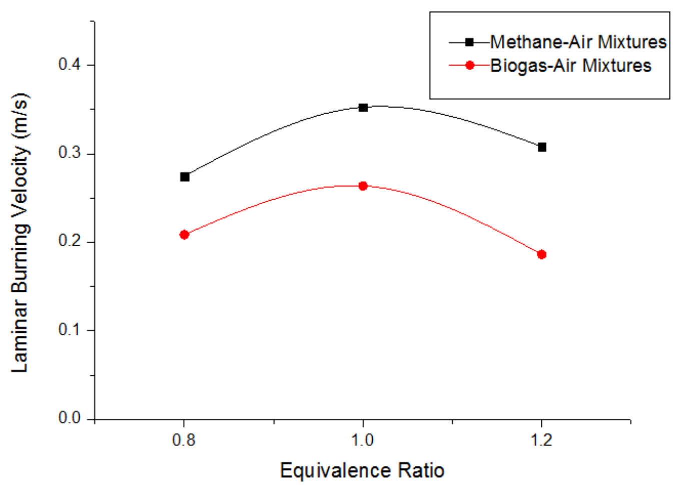

Fig. 10: Laminar Burning Velocities of Methane-Air Mixtures and Biogas-Air Mixtures.

From Table 2 and Fig. 10, it can be seen that laminar burning velocities of stoichiometric (□=1) biogas-air mixtures and methane-air mixtures were higher than the lean and rich mixtures because the stoichiometric mixtures had just enough air for complete combustion of the available fuel. As expected, because the presence of carbon dioxide and nitrogen in the biogas, at the same equivalence ratio, the laminar burning velocity of biogas-air mixtures is lower than the laminar burning velocitiy of the methane-air mixtures. The carbon dioxide and nitrogen in the biogas are inhibitors that tend to decrease the laminar burning velocities (Ronney, P.D., 2001). The mechanism of inhibition is a combination of two effects. There is a dilution effect such that the energy generated from the fuel oxidation has a greater quantity of gas to heat, thus lowering the flame temperature and thus reducing the overall rate of chemical reactions within the flame that have a positive temperature dependence. The dilution effect also leads to a reduction in the fuel concentration and by implication a reduction in the concentration of reactive species during the fuel oxidation process, which again reduces the overall rate of bimolecular chemical reactions within the flame.

The difference between the values of laminar burning velocities of methane-air mixtures and biogas-air mixtures at equivalence ratios of 0.8, 1.0, and 1.2 are shown in Fig. 11. Increasing the equivalence ratio of mixtures increased this difference, because at the higher equivalence ratios the inhibitor gases (carbon dioxide and nitrogen) from the biogas form a higher mole fraction of the overall mixture than is the case at the low equivalence ratios, thus leading to an increase in the dilution effect that they cause.

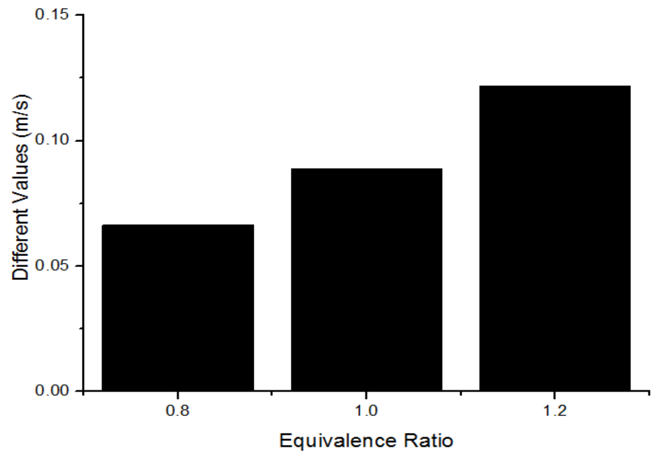

Fig. 11: Differences between Laminar Burning Velocities of Methane-Air Mixtures and Biogas-Air Mixtures as A Function of Equivalence Ratio.

A subtle effect on the laminar burning velocity as a function of equivalence ratio can be observed in Fig. 10, the laminar burning velocity in a rich (□=1.2) methane-air mixture was higher than that of a lean (□=0.8) methane-air mixture, and this is the typical characteristic of common hydrocarbon fuels (Anggono W., 2012; Gu. X.J., 2000; Bradley D., 1998; Liao S.Y., 2006;2004; Miao H., 2009; Metghalchi, M., 1980). In contrast, the laminar burning velocity of a rich (□=1.2) biogas-air mixture was lower than that of lean (□=0.8) mixture, as shown in Fig.12. This reinforces the observation that the effect of inhibitor gases in biogas on the laminar burning velocities was higher at rich mixtures than that at lean ones due to the higher mole fraction of these inhibitor gases. A consequence is that the optimum equivalence ratio for the operation of biogas-air fuel mixtures is shifted towards a leaner mixture than would be the case for a pure methane fuel mixture.

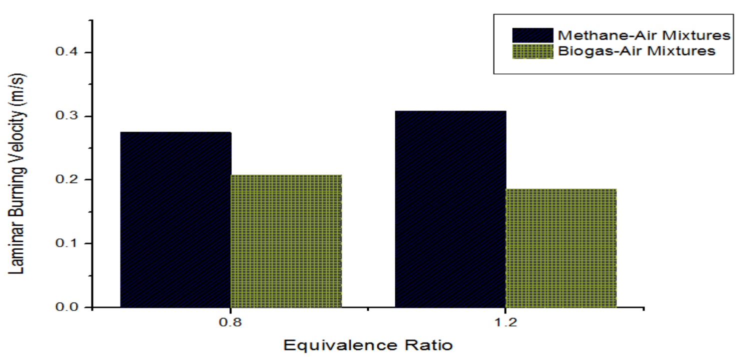

Fig. 12: Laminar Burning Velocities Methane-Air Mixtures and Biogas-Air Mixtures Comparison Results for Lean (□=0.8) and Rich (□=1.2) Mixtures.

Conclusions:

The laminar burning velocities of biogas-air mixtures were 0.2086 m/s for lean (□=0.8), 0.2638 m/s for stoichiometric (□=1.0) and 0.1864 m/s for rich (□=1.2) conditions. The laminar burning velocities of biogas-air mixtures were lower than those in methane-air mixtures at the same equivalence ratio because biogas contains carbon dioxide and nitrogen which are flame inhibitors. These absorb some of the energy released from fuel combustion thus lowering the flame temperature, and also dilute the chemically reactive species in the flame, hence reducing the laminar burning velocity. The increasing mole fraction in the fuel-air mixture of the carbon dioxide and nitrogen from the biogas as the equivalence ratio increases, causes their inhibiting effect to increase in importance in rich mixtures. As a consequence, this shifts the optimum equivalence ratio for biogas-air combustion to a leaner mixture than is the case in methane-air combustion.

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